Using CFD To Assess The Impact of Helical Baffle On The First- Law And Second-Law Performance of Water-CuO Nanofluid Inside A Hairpin Heat Exchanger

Amin Shahsavari

Kermanshah University of Technology

Davood Toghraie (✉ Toghraee@iaukhsh.ac.ir)

Islamic Azad University

Pouya Barnoon

Islamic Azad University

Research Article

Keywords: Numerical simulation, Heat exchanger, Turbulator, Nanofluid, Irreversibility

Posted Date: September 8th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-877881/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Using CFD to assess the impact of helical baffle on the first-law and second-law performance of water-CuO nanofluid inside a hairpin heat exchanger

Amin Shahsavari¹, Davood Toghraie^{*2}, Pouya Barnoon²

¹ Department of Mechanical Engineering, Kermanshah University of Technology, Kermanshah, Iran

² Department of Mechanical Engineering, Khomeinishahr Branch, Islamic Azad University, Isfahan, Iran

***Corresponding author Email:** Toghraee@iaukhsh.ac.ir

Abstract

This study is devoted to the numerical assessment of the influence of helical baffle on the hydrothermal aspects and irreversibility behavior of the turbulent forced convection flow of water-CuO nanofluid (NF) inside a hairpin heat exchanger. The variations of the first-law and second-law performance metrics are investigated in terms of Reynolds number (Re), volume concentration of NF (ϕ) and baffle pitch (B). The results showed that the NF Nusselt number grows the rise of both the Re and ϕ whereas it declines by boosting with the rise of baffle pitch. In addition, the outcomes depicted that the rise of both the Re and ϕ results in the rise of pressure drop, while it declines with the increase of baffle pitch. Moreover, it was found that the best first-law performance of the NF belongs to the case $B=33.3$ mm, $\phi=2\%$ and $Re_{nf}=10000$. Furthermore, it was shown that irreversibilities due to fluid friction and heat transfer augment with the rise of Re while the rise of baffle pitch results in the decrease of frictional irreversibilities. Finally, the outcomes revealed that with the rise of baffle pitch, the heat transfer irreversibilities first intensifies and then diminishes.

Keywords: Numerical simulation; Heat exchanger; Turbulator; Nanofluid; Irreversibility.

1. Introduction

It is well known that the turbulent flow has a higher heat exchange and pumping power than the laminar flow, the former being desirable and the latter undesirable. So, the idea came into the researchers' minds to put equipment in the path of laminar flow and create local turbulence. The idea was very successful and has been widely used in the industry today. This equipment is called turbulator, and so far, various types of turbulators have been introduced and their performance has been studied experimentally and numerically [1-10].

Although the use of turbulators has led to an improvement in the performance of heat transfer systems, this has not prevented researchers from looking for ways to further improve the performance of these systems. One of these amazing techniques, which originated from the low thermal conductivity of heat transfer fluids, is nanofluid (NF). Choi [11] first made these modern fluids and called them NFs. After the introduction of NFs and their amazing thermal properties, much research has been done on their performance in diverse applications [12-15].

The literature inspection shows that the performance of thermal systems with NF coolants equipped with turbulators has been investigated by various researchers. Bellos et al. [16] analyzed the efficacy of oil-CuO NF in a parabolic trough collector equipped with turbulators. They found that using the combination of NF and turbulator causes a 1.54% thermal efficiency improvement. Nakhchi and Esfahani [17] inspected the efficacy of aqueous Cu NF inside a heated tube equipped with perforated conical rings in a turbulent regime. It was reported that using compound NF and turbulator results in a considerable heat transfer intensification. Akyurek et al. [18] experimentally evaluated the forced convection flow of water- Al_2O_3 NF inside a horizontal tube equipped with wire coil turbulator. They utilized two turbulators with different pitches and found that the performance metrics of tube filled with NF without any turbulator is

superior to that of the cases with turbulator. Xiong et al. [19] simulated the efficacy of aqueous CuO NF flowing inside a tube having a compound turbulator. The outcomes portrayed that using turbulator elevates the rate of heat exchange between tube wall and NF. Xiong et al. [20] numerically investigated the forced convection of NF through a pipe equipped with a complex-shaped turbulator. They inspected the consequence of elevating width ratio, flow rate and pitch ratio on the performance features. It was found that the Nusselt number intensifies with boosting pitch ratio of turbulator. In a numerical investigation, Ahmed et al. [21] explored the forced convection of water- Al_2O_3 and water-CuO NFs inside a triangular duct with a delta-winglet pair of turbulator under turbulent flow regime. They reported the significant effect of using both NF and turbulator on the performance aspects.

The design of a heat transfer system can be done both according to the first-law or the second-law of thermodynamics. If the first-law applies, the system must have the highest overall hydrothermal performance, and if the second-law applies, the system performance must have the least irreversibility. The efficacy of NF flow in turbulator-equipped thermal units has rarely been investigated from a second-law perspective [22-25]. Sheikholeslami et al. [22] inspected the irreversibility features of turbulent flow of aqueous CuO NF inside a pipe equipped with complex turbulators. Li et al. [23] simulated the NF irreversibility in a tube with helical twisted tapes. The thermal irreversibility was found to be declined with elevating the height ratio of turbulator, while the opposite is true for the frictional irreversibility. Farshad and Sheikholeslami [24] analyzed the irreversibility aspects for aqueous Al_2O_3 NF flow in a solar collector having a twisted tape. The outcomes revealed that the irreversibility diminishes with the increase of diameter ratio. Al-Rashed et al. [25] examined the influence of nanomaterials type on the

irreversibility production of a NF in a heat exchanger. It was reported that the maximum irreversibility belongs to the platelet shape nanomaterials.

The aim of this numerical work is to evaluate the features of turbulent flow of a NF through a hairpin heat exchanger equipped with helical baffles in the annulus side from both the first and second-law perspectives. The impacts of baffle pitch, Re and φ on the NF efficacy are assessed. This investigation is the first work on the consequences of using helical baffle on the irreversibility production inside an annulus of a hairpin heat exchanger filled with NF.

2. Problem statement

Fig. 1 gives a demonstrative sketch of geometry under investigation. It is a hairpin heat exchanger with 100 mm length, 10 mm inner tube internal diameter, and 15 mm outer diameter internal diameter. Additionally, the wall thickness for both the inner and outer tubes is 1 mm. Moreover, the baffle pitch varies from 25 mm to 100 mm.

The purpose of using this device is to cool the NF passing through the annulus with the help of water passing through the inner tube. In both water and nanofluid streams, time is of the essence and both streams are in turbulent regime. Both streams enter the device at a uniform velocity and temperature and are discharged into the atmosphere. Also, the exterior wall of heat exchanger is considered as insulated and no slip condition is utilized on the walls.

(a) $B=25$ mm

(b) $B=33$ mm

(c) $B=50$ mm

(d) $B = 100$ mm

(e) 2-D view

Fig. 1. Schematic sketch of the problem.

3. Governing equations and problem parameters

Continuity equation

$$\frac{\partial(u_i)}{\partial x_i} = 0 \quad (1)$$

Momentum equation

$$\frac{\partial}{\partial x_j} (u_j \rho_{nf} u_i) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu_{nf} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + \frac{\partial}{\partial x_j} (-\rho_{nf} \overline{u'_j u'_i}) \quad (2)$$

Energy equation

$$\frac{\partial}{\partial x_i} (\rho_{nf} T u_i) = \frac{\partial}{\partial x_i} \left[(\mu_t / Pr_t + \mu_{nf} / Pr_{nf}) \frac{\partial T}{\partial x_i} \right] \quad (3)$$

115 where μ_t and $\rho_{nf}\overline{u'_j u'_l}$ are defines as follows;

$$116 \quad \mu_t = \rho_{nf} C_\mu k^2 / \varepsilon \quad (4)$$

$$117 \quad \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \delta_{ij} \left(\rho_{nf} k + \mu_t \frac{\partial u_k}{\partial x_k} \right) = -\rho_{nf} \overline{u'_j u'_l} \quad (5)$$

118 k & ε parameters are defined as follows;

$$119 \quad \frac{\partial}{\partial x_j} \left[\frac{\partial k}{\partial x_j} \left(\mu_{nf} + \frac{\mu_t}{\sigma_k} \right) \right] - \rho_{nf} \varepsilon + G_k = \frac{\partial}{\partial x_i} (u_i \rho_{nf} k) \quad (6)$$

120 where

$$121 \quad G_k = -\frac{\partial u_j}{\partial x_i} \rho_{nf} \overline{u'_j u'_l} \quad (7)$$

$$122 \quad \frac{\partial}{\partial x_i} (\rho_{nf} u_i \varepsilon) = \frac{\partial}{\partial x_j} \left[\frac{\partial \varepsilon}{\partial x_j} \left(\mu_{nf} + \frac{\mu_t}{\sigma_\varepsilon} \right) \right] + \frac{\varepsilon}{k} G_k C_{1\varepsilon} - \rho_{nf} \frac{\varepsilon^2}{k} C_{2\varepsilon} \quad (8)$$

123 where

$$124 \quad Pr_t = 0.85; C_\mu = 0.0845; \sigma_k = 1; \sigma_\varepsilon = 1.3; C_{1\varepsilon} = 1.42; C_{2\varepsilon} = 1.68.$$

125 The irreversible generation in forced convection flow of NF flow is due to two sources, namely
126 fluid friction and heat exchange. Therefore, the total irreversibility is computed as:

$$127 \quad S_{gen} = \underbrace{\frac{\mu_{nf}}{T_0} \left\{ 2 \left[\left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial y} \right)^2 + \left(\frac{\partial w}{\partial z} \right)^2 \right] + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right)^2 + \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right)^2 \right\}}_{S_{gen,f}} \\ 128 \quad + \underbrace{\frac{k_{nf}}{T_0^2} + \left[\left(\frac{\partial T}{\partial x} \right)^2 + \left(\frac{\partial T}{\partial y} \right)^2 + \left(\frac{\partial T}{\partial z} \right)^2 \right]}_{S_{gen,t}} \quad (9)$$

130 By integrating the whole computational domain, the total irreversibility can be obtained:

$$131 \quad S_{tot} = \int S_{gen} dv \quad (10)$$

132 *Bejan number:*

$$133 \quad Be = \frac{S_{gen,t}}{S_{tot}} \quad (11)$$

134 The characteristic of a NF includes its thermo-physical properties that establish the relationship
 135 between the base fluid and the nanoparticles. These basic relationships are defined as follows
 136 [28-33]:

$$137 \quad \rho_m = \rho_f(1 - \varphi) + \rho_p\varphi \quad (12)$$

$$138 \quad (\rho C_p)_m = (\rho C_p)_f(1 - \varphi) + (\rho C_p)_p\varphi \quad (13)$$

$$139 \quad k_{nf} = k_f \frac{k_p + 2k_f + 2\varphi(k_p - k_f)}{k_p + 2k_f - \varphi(k_p - k_f)} \quad (14)$$

$$140 \quad \mu_{nf} = (123\varphi^2 + 7.3\varphi + 1)\mu_{bf} \quad (15)$$

141 The heat transfer rates for hot and cold fluids are calculated as follows:

$$142 \quad q_h = \dot{m}_h C_{p,h} (T_{h,i} - T_{h,o}) \quad (16)$$

$$143 \quad q_c = \dot{m}_c C_{p,c} (T_{c,i} - T_{c,o}) \quad (17)$$

144 *Average Nusselt number:*

$$145 \quad Nu = \frac{hD_h}{k_f} \quad (18)$$

146 *The heat transfer coefficient [34-35]:*

$$147 \quad h = \frac{q''}{\Delta T_{LMTD}} \quad (19)$$

148 where:

$$149 \quad \Delta T_{LMTD} = \frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2 / \Delta T_1)} \quad (20)$$

150 where;

$$151 \quad \Delta T_2 = T_{h,o} - T_{c,i} \quad (21)$$

$$152 \quad \Delta T_1 = T_{h,i} - T_{c,o} \quad (22)$$

153 q'' is the total heat flux that the fluid receives over the entire computational domain and is
154 calculated as [28, 29]:

$$155 \quad q'' = \frac{1}{A} \int q''(x) dx \quad (23)$$

156 The pressure drop (ΔP) is defined as follows:

$$157 \quad \Delta P = f \frac{L}{D_h} \frac{\rho u^2}{2} \quad (24)$$

158 Thermal performance can be computed as:

$$159 \quad \eta = \frac{q}{\Delta P} \quad (25)$$

160

161 **4. Numerical scheme, validation and Grid independency**

162 In the current numerical investigation, the simulations are conducted using the ANSYS Fluent
163 18.1 software. The governing equations are discretized using the second-order upwind technique.
164 Besides, the SIMPLE scheme is utilized to perform the pressure-velocity coupling. The
165 convergence metric is set to 10^{-6} .

166 Four different types of grids are used to make the outputs of the problem independent of the
167 mesh. Tetrahedral mesh is used. The walls have a boundary layer mesh with a factor of 5%. The
168 Nusselt number is used to perform the mesh study. Finally, it was found that the most
169 appropriate mesh is the one with 650538 element number.

170 To ensure the accuracy and validity of the results of present work, the experimental findings of
171 Wen and Ding [37] and the numerical outcomes of Goktepe et al. [38] for the local convection
172 coefficient of NF flowing through a uniformly heated tube are employed. The outcomes are

reported in Fig. 2. As can be observed, there is a good consistency between the outcomes and the largest discrepancy between our results and the data from the other works (i.e. Refs. [37, 38]) is 10%.

To further validate the simulations, the average Nusselt number of NF flow inside a channel with rectangular rib (in-line) reported by Vanaki and Mohammed [39] is compared with our results. As can be seen in Fig. 3, at low velocities, a good consistency is observed, and as the flow velocity elevates, the discrepancy of the results is elevated and reaches to 7%.

Fig. 2. Validation with experimental [37] and numerical [38] works.

Fig. 3. Validation with numerical work [39].

5. Results and Discussion

The main focus of this numerical investigation is to analyze the turbulent flow of water-CuO NF inside a hairpin heat exchanger with helical baffle in the annulus side. The effects of φ (0-4%), Re (5000-10000) and baffle pitch (25-100 mm) on the performance metrics are investigated.

Fig. 4 depicts the contour plots of NF velocity and temperature for different helical baffle pitches at $Re_{nf} = 5000$ and $\varphi = 4\%$. It is seen that as baffle pitch augments, the NF velocity diminishes.

$B = 25 \text{ mm}$

$B = 33 \text{ mm}$

$B = 50 \text{ mm}$

Fig. 4. Contours of NF velocity (left) and temperature (right) in terms of baffle pitch at $Re_{nf} = 5000$ and $\varphi = 4\%$.

195

196 Fig. 5 gives the consequences of elevating Re on the velocity and temperature contours of NF for
 197 baffle pitch of 25 mm. As is seen, intensifying the Re entails an elevation in the NF velocity and
 198 a decrement in the NF temperature.

199

Fig. 5. Contours of NF velocity (left) and temperature (right) in terms of Re for $B = 25$ mm.

200

201 Fig. 6 gives the Nusselt number in terms of baffle pitch for various φ . The Nusselt number
 202 improves by elevating both the Re and φ , while it declines by augmenting the baffle pitch. For
 203 instance, at $Re_{nf} = 5000$ and $\varphi = 0\%$, elevating the baffle pitch from 25 to 100 mm results in a
 204 19.05% decrease in the Nusselt number of NF, while this amount for $\varphi = 4\%$ is 15.62%. In
 205 addition, at baffle pitch of 25 mm and $\varphi = 4\%$, intensification of Re from 5000 to 10000 causes
 206 a 61.83% decline in the Nusselt number of NF. Elevating the Re entails a rise in the thickness of
 207 the velocity and thermal boundary layer, which elevates the temperature gradient and,
 208 consequently, elevates the convective heat transfer coefficient and Nusselt number. Moreover,
 209 intensification of φ causes an augmentation in the k_{nf} and, thereby, an augmentation in the

210 convective heat transfer and Nusselt number. Furthermore, intensifying the baffle pitch entail a
 211 decrease in the NF velocity and, therefore, a decrease in the convective heat transfer coefficient
 212 and Nusselt number.

(a)

(b)

(c)

Fig. 6. Variations of Nusselt number versus baffle pitch in terms of φ for (a) $Re_{nf} = 5000$, (a) $Re_{nf} = 7500$ and
(a) $Re_{nf} = 10000$.

213

214

215

216

217

218

219

220

221

222

223

224

One of the important issues when choosing a working fluid is that the fluid performance should be examined from both the heat transfer and pressure drop (pumping power) aspects. Fig. 7 gives the variations of the pressure drop of NF versus φ and baffle pitch for different Re . It is observed that the pressure drop intensifies by boosting both the φ and Re , while it reduces by boosting the baffle pitch. For example, at $Re_{nf} = 5000$ and $\varphi = 0\%$, boosting the baffle pitch from 25 to 100 mm results in a 73.59% reduction in the pressure drop of NF, while this amount for $\varphi = 4\%$ is 73.55%. Additionally, at baffle pitch of 25 mm and $\varphi = 4\%$, augmentation of Re from 5000 to 10000 results in a 232.82% decrease in the pressure drop of NF. Boosting both the Re and φ causes an elevation in the NF velocity and, therefore, according to Eq. (), the pressure drop of NF elevates. On the other hand, elevating the baffle pitch causes an increment in the annulus fluid path and, as a result, an elevation in the pressure drop, while the NF velocity declines by

225 boosting the baffle pitch which results in a decrease in the pressure drop of NF. According to the
 226 obtained results, it can be concluded the effect of elevated annulus flow path on the pressure
 227 drop outweighs the effect of decreases NF velocity and, therefore, the NF pressure drop reduces
 228 with an elevation in the baffle pitch.

229

(a)

Fig. 7. Variations of pressure drop versus baffle pitch in terms of φ for (a) $Re_{nf} = 5000$, (a) $Re_{nf} = 7500$ and
(a) $Re_{nf} = 10000$.

230

231 The results presented so far have shown that intensifying the φ entails an elevated Nusselt
232 number and pressure drop, which the first is a favorable effect and the latter is undesirable. For
233 the final decision on the usefulness of using NF in the heat exchanger under investigation, the
234 performance index should be examined. Fig. 8 demonstrates the variations of the performance
235 index versus φ and baffle pitch for different Re . The outcomes reveal that the hydrodynamic
236 performance of the water-CuO NF in the considered heat exchanger is superior to that of the pure
237 water in just the following four cases:

- 238 • $B = 100$ mm, $\varphi = 4\%$ and $Re_{nf} = 5000$ where $\eta = 1.029$.
- 239 • $B = 33.3$ mm, $\varphi = 2\%$ and $Re_{nf} = 10000$ where $\eta = 1.067$.
- 240 • $B = 33.3$ mm, $\varphi = 4\%$ and $Re_{nf} = 10000$ where $\eta = 1.054$.

241 • $B = 100$ mm, $\varphi = 2\%$ and $Re_{nf} = 10000$ where $\eta = 1.000$.

242

(a)

(b)

(c)

Fig. 8. Variations of performance index versus baffle pitch in terms of ϕ for (a) $Re_{nf} = 5000$, (a) $Re_{nf} = 7500$ and (a) $Re_{nf} = 10000$.

243

244

245

246

247

248

249

250

251

252

253

254

In the remainder of this section, the flow of water-CuO NF with $\phi = 2\%$ in the considered heat exchanger is examined from the perspective of irreversibility production. Fig. 9 displays the influences of Re and baffle pitch on the frictional irreversibility of NF. As can be seen, the frictional irreversibility declines and rises with increasing baffle pitch and Re , respectively, and the Re effect on the frictional irreversibility at lower baffle pitch is greater. For example, at $Re = 5000$, increasing the baffle pitch from 25 to 100 mm results in a 67.84% decrease in the frictional irreversibility. In addition, at $B = 100$ mm, the augmentation of Re from 5000 to 10000 causes a 209.45% increment in the frictional irreversibility. By boosting the Re at a constant ϕ (i.e. constant Prandtl number) and baffle pitch, the thickness of the velocity boundary layer decreases, which results in an elevated velocity gradient and thus an elevated frictional irreversibility. On the other hand, increasing the Re at a constant ϕ and baffle pitch, results in an

elevated NF velocity and hence a decrease in the average NF temperature which results in an elevated frictional irreversibility. Elevating the baffle pitch results in a decrease in the flow mixing, which results in a decrease in the velocity gradient and a decrease in the NF temperature, which in turn decreases and elevates the frictional irreversibility. It can be concluded that the decreasing effect of velocity gradient on the frictional irreversibility is overcome by the increasing effect of NF temperature and, therefore, the frictional irreversibility decreases with increasing baffle pitch.

Fig. 9. Variations of frictional irreversibility of NF with $\phi = 2\%$ versus baffle pitch in terms of Re .

Fig. 10 gives the changes of thermal irreversibility of NF with $\phi = 2\%$ versus baffle pitch in terms of Re . It is seen that the thermal irreversibility declines with the elevation of Re . For example, at $B = 100$ mm, the intensification of Re from 5000 to 10000 causes a 52.57% decrease in the thermal irreversibility. As mentioned before, the NF temperature decreases with increasing Re at a constant ϕ and baffle pitch, which results in an elevated thermal

irreversibility. Also, the augmentation of Re results in improved mixing of the flow and consequently, a decrease in the temperature gradient which ultimately results in a decrease in the thermal irreversibility. It can be said that the impact of temperature gradient on the thermal irreversibility outweighs the impact of NF temperature and therefore, the thermal irreversibility declines with the rise of Re . Moreover, Fig. 10 shows that with the rise of baffle pitch at a constant Re and ϕ , the thermal irreversibility first elevates and then reduces. The highest thermal irreversibility occurs at baffle pitch of 50 mm. Boosting of baffle pitch at a constant ϕ and Re reduces the flow mixing which results in the decrease of both the NF temperature and temperature gradient which respectively elevates and diminishes the rate of thermal irreversibility. Fig. 10 reveals that for the baffle pitch lower than 50 mm, the increasing impact of temperature outweighs the decreasing of temperature gradient and ultimately, the thermal irreversibility declines while the opposite is true for the baffle pitch higher than 50 mm.

Fig. 10. Variations of thermal irreversibility of NF with $\phi = 2\%$ versus baffle pitch in terms of Re .

The results presented in Figs. 9 and 10 show that increasing the baffle pitch results in a decrease in both the thermal and frictional irreversibilities, and therefore, it can be easily deduced that increasing the baffle pitch entails a declined total irreversibility. However, the influence of Re on the total irreversibility cannot be predicted because the thermal irreversibility elevates with decreasing Re and then decreases. Fig. 11 displays the variations of total irreversibility versus baffle pitch in terms of Re . For the baffle pitch of lower than 50 mm, the rise of Re entails an elevated total irreversibility whereas for the baffle pitch of 100 mm, the total irreversibility first elevates with the rise of Re and then decreases. The lowest total irreversibility occurs at $Re = 7500$ and $B = 100$ mm.

Fig. 11. Variations of thermal irreversibility of NF with $\phi = 2\%$ versus baffle pitch in terms of Re .

At the end of this section, we examine how each of the frictional and thermal entropies contribute to the total irreversibility. To investigate this problem, the variations of the Bejan number with the baffle pitch and Re are assessed. As can be seen in Fig. 12, the Bejan number of NF augments with the grow of baffle pitch and decline of Re . It is therefore concluded that the

contribution of thermal irreversibility to total irreversibility is higher in lower Re and higher baffle pitch.

Fig. 12. Variations of Bejan number of NF with $\phi = 2\%$ versus baffle pitch in terms of Re .

6. Conclusion

In this study, the first-law and the-second law of thermodynamics are employed to investigate the turbulent flow of aqueous CuO NF through a hairpin heat exchanger equipped with helical baffle in the annulus side. The influence of Re (5000-10000), ϕ (0-4%) and baffle pitch (25-100 mm) on the performance metrics are assessed. The following results can be deduced from this simulation:

- With the rise of baffle pitch at a constant Re and ϕ , the thermal irreversibility first elevates and then reduces.
- Intensifying the Re entails an elevated NF velocity and a declined NF temperature.

- Pressure drop intensifies by boosting both the φ and Re , while it reduces by boosting the baffle pitch.
- Frictional irreversibility declines and rises with increasing baffle pitch and Re , respectively.
- Re effect on the frictional irreversibility at lower baffle pitch is greater.

References

- [1] M.S. Nazir, A. Shahsavar, M. Afrand, M. Arici, S. Nizetic, Z. Ma, H.F. Oztop, A comprehensive review of parabolic trough solar collectors equipped with turbulators and numerical evaluation of hydrothermal performance of a novel model, Sustainable Energy Technologies and Assessments 45 (2021) 101103.
- [2] S. Rostami, A. Shahsavar, G.R. Kefayati, A. Shahsavar Goldanlou, Energy and exergy analysis of using turbulator in a parabolic trough solar collector filled with mesoporous silica modified with copper nanoparticles hybrid nanofluid, Energies 13 (2020) 2946.
- [3] M.B. Elsheniti, M.O. Elbessomy, K. Wagdy, O.A. Elsamni, M.M. Elewa, Augmenting the distillate water flux of sweeping gas membrane distillation using turbulators: A numerical investigation, Case Studies in Thermal Engineering 26 (2021) 101180.
- [4] Q. Xiong, M. Izadi, M. Shokri rad, S.A. Shehzad, H.A. Mohammed, 3D Numerical Study of Conical and Fusiform Turbulators for Heat Transfer Improvement in a Double-Pipe Heat Exchanger, International Journal of Heat and Mass Transfer 170 (2021) 120995.
- [5] M.E. Nakhchi, M. Hatami, M. Rahmati, Effects of CuO nano powder on performance improvement and entropy production of double-pipe heat exchanger with innovative perforated turbulators, Advanced Powder Technology 32 (2021) 3063-3074.

333 [6] Y. Khetib, H. Sait, B. Habeebullah, A. Hussain, Numerical study of the effect of curved
334 turbulators on the exergy efficiency of solar collector containing two-phase hybrid nanofluid,
335 Sustainable Energy Technologies and Assessments 47 (2021) 101436.

336 [7] I. Bashtani, J.A. Esfahani, K.C. Kim, Effects of water-aluminum oxide nanofluid on double
337 pipe heat exchanger with gear disc turbulators: A numerical investigation, Journal of Taiwan
338 Institute of Chemical Engineers 124 (2021) 63-74.

339 [8] H.A. Mohammed, H.B. Vuthaluru, S. Liu, Heat transfer augmentation of parabolic trough
340 solar collector receiver's tube using hybrid nanofluids and conical turbulators, Journal of Taiwan
341 Institute of Chemical Engineers 125 (2021) 215-242.

342 [9] M. Jafaryar, M. Sheikholeslami, R. Moradi, Nanofluid turbulent flow in a pipe under the
343 effect of twisted tape with alternate axis, Journal of Thermal Analysis and Calorimetry 135
344 (2019) 305-323.

345 [10] M. Khoshbaght-Aliabadi, M. Farsi, S.M. Hassani, N.H. Abu-Hamdeh, A. Alimoradi,
346 Surface modification of transversely twisted-turbulator using perforations and winglets: An
347 extended study, International Communications in Heat and Mass Transfer 120 (2021) 105020.

348 [11] S.U.S. Choi, Enhancing thermal conductivity of fluids with nanoparticles, ASME FED 231
349 (1995) 99-105.

350 [12] A.H. Pordanjani, S. Aghakhani, M. Afrand, B. Mahmoudi, O. Mahian, S. Wongwises, An
351 updated review on application of nanofluids in heat exchangers for saving energy, Energy
352 Conversion and Management 198 (2019) 111886.

353 [13] A. Shahsavari, M. Jamei, M. Karbasi, Experimental evaluation and development of
354 predictive models for rheological behavior of aqueous Fe₃O₄ ferrofluid in the presence of an

external magnetic field by introducing a novel grid optimization based-Kernel ridge regression supported by sensitivity analysis, *Powder Technology* 393 (2021) 1-11.

[14] A. Shahsavar, M. Shahmohammadi, E.B. Askari, CFD simulation of the impact of tip clearance on the hydrothermal performance and entropy generation of a water-cooled pin-fin heat sink, *International Communications in Heat and Mass Transfer* 126 (2021) 105400.

[15] A. Shahsavar, M. Rashidi, C. Yildiz, M. Arici, Natural convection and entropy generation of Ag-water nanofluid in a finned horizontal annulus: A particular focus on the impact of fin numbers, *International Communications in Heat and Mass Transfer* 125 (2021) 105349.

[16] E. Bellos, C. Tzivanidis, D. Tsimpoukis, Enhancing the performance of parabolic trough collectors using nanofluids and turbulators, *Renewable and Sustainable Energy Reviews* 91 (2018) 358-375.

[17] M.E. Nakhchi, J.A. Esfahani, Numerical investigation of turbulent Cu-water nanofluid in heat exchanger tube equipped with perforated conical rings, *Advanced Powder Technology* 30 (2019) 1338-1347.

[18] E.F. Akyurek, K. Gelis, B. Sahin, E. Manay, Experimental analysis for heat transfer of nanofluid with wire coil turbulators in a concentric tube heat exchanger, *Results in Physics* 9 (2018) 376-389.

[19] Q. Xiong, M. Jafaryar, A. Divsalar, M. Sheikholeslami, A. Shafee, D.D. Vo, M.H. Khan, I. Tlili, Z. Li, Macroscopic simulation of nanofluid turbulent flow due to compound turbulator in a pipe, *Chemical Physics* 527 (2019) 110475.

[20] Q. Xiong, M. Ayani, A.A. Barzinjy, R.N. Dara, A. Shafee, T. Nguyen-Thoi, Modeling of heat transfer augmentation due to complex-shaped turbulator using nanofluid, *Physica A* 540 (2020) 122465.

378 [21] H.E. Ahmed, M.Z. Yusoff, M.N.A. Hawlader, M.I. Ahmed, B.H. Salman, A.Sh. Kerbeet,
 379 Turbulent heat transfer and nanofluid flow in a triangular duct with vortex generators,
 380 International Journal of Heat and Mass Transfer 105 (2017) 495-504.

381 [22] M. Sheikholeslami, M. Jafaryar, J.A. Ali, S.M. Hamad, A. Divsalar, A. Shafee, T. Nguyen-
 382 Thoi, Z. Li, Simulation of turbulent flow of nanofluid due to existence of new effective
 383 turbulator involving entropy generation, Journal of Molecular Liquids 291 (2019) 111283.

384 [23] Z. Li, M. Sheikholeslami, M. Jafaryar, A. Shafee, A.J. Chamkha, Investigation of nanofluid
 385 entropy generation in a heat exchanger with helical twisted tapes, Journal of Molecular Liquids
 386 266 (2018) 797-805.

387 [24] S.A. Farshad, M. Sheikholeslami, Nanofluid flow inside a solar collector utilizing twisted
 388 tape considering exergy and entropy analysis, Renewable Energy 141 (2019) 246-258.

389 [25] A.A.A.A. Al-Rashed, R. Ranjbarzadeh, S. Aghakhani, M. Soltanimehr, M. Afrand, T.K.
 390 Nguyen, Entropy generation of boehmite alumina nanofluid flow through a minichannel heat
 391 exchanger considering nanoparticle shape effect, Physica A 521 (2019) 724-736.

392 [26] P. Barnoon, D. Toghraie, F. Eslami, B. Mehmandoust, Entropy generation analysis of
 393 different nanofluid flows in the space between two concentric horizontal pipes in the presence of
 394 magnetic field: Single-phase and two-phase approaches, Computers & Mathematics with
 395 Applications 77 (2019) 662-692.

396 [27] P. Barnoon, D. Toghraie, R.B. Dehkordi, H. Abed, MHD mixed convection and entropy
 397 generation in a lid-driven cavity with rotating cylinders filled by a nanofluid using two phase
 398 mixture model, Journal of Magnetism and Magnetic Materials 483 (2019) 224-24.

- 399 [28] Z. Li, P. Barnoon, D. Toghraie, R.B. Dehkordi, M. Afrand, Mixed convection of non-
 400 Newtonian nanofluid in an H-shaped cavity with cooler and heater cylinders filled by a porous
 401 material: Two phase approach, *Advanced Powder Technology* 30 (2019) 2666-2685.
- 402 [29] P. Barnoon, D. Toghraie, R.B. Dehkordi, M. Afrand, Two phase natural convection and
 403 thermal radiation of Non-Newtonian nanofluid in a porous cavity considering inclined cavity and
 404 size of inside cylinders, *International Communications in Heat and Mass Transfer* 108 (2019)
 405 104285.
- 406 [30] J.C. Maxwell, *Treatise on electricity and magnetism*, Oxford: Clarendon Press, 1873.
- 407 [31] H. Brinkman, The viscosity of concentrated suspensions and solutions, *The journal of*
 408 *chemical physics* 20 (1952) 571-577.
- 409 [32] B.C. Pak, Y.L. Cho, Hydrodynamic and heat transfer study of dispersed fluids with
 410 submicron metallic oxide particles, *Experimental Heat Transfer an International Journal* 11
 411 (1998) 141-170.
- 412 [33] Y. Xuan, W. Roetzel, Conceptions for heat transfer correlation of nanofluids, *International*
 413 *Journal of Heat and Mass Transfer* 43 (2000) 3701-3707.
- 414 [34] M. Bahiraei, A. Godini, A. Shahsavar, Thermal and hydraulic characteristics of a
 415 minichannel heat exchanger operated with a non-Newtonian hybrid nanofluid, *Journal of the*
 416 *Taiwan Institute of Chemical Engineers* 84 (2018) 149-161.
- 417 [35] J. Alsarraf, A. Moradikazerouni, A. Shahsavar, M. Afrand, M.D. Tran, Hydrothermal
 418 analysis of turbulent boehmite alumina nanofluid flow with different nanoparticle shapes in a
 419 minichannel heat exchanger using two-phase mixture model, *Physica A* 520 (2019) 275-288.

420 [36] A. Karimi, A.A.A.A. Al-Rashed, M. Afrand, O. Mahian, A. Shahsavar, The effects of tape
 421 insert material on the flow and heat transfer in a nanofluid-based double tube heat exchanger:
 422 Two-phase mixture model, *International Journal of Mechanical Sciences* 156 (2019) 397-409.

423 [37] D. Wen, Y. Ding, Experimental investigation into convective heat transfer of nanofluids at
 424 the entrance region under laminar flow conditions, *International Journal of Heat and Mass*
 425 *Transfer* 47 (2004) 5181–5188.

426 [38] S. Göktepe, K. Atalık, H. Ertürk, Comparison of single and two-phase models for nanofluid
 427 convection at the entrance uniformly heated tube, *International Journal of Thermal Sciences* 80
 428 (2014) 83–92.

429 [39] S.M. Vanaki, H.A. Mohammed, Numerical study of nanofluid forced convection flow in
 430 channels using different shaped transverse ribs, *International Communications in Heat and Mass*
 431 *Transfer* 67 (2015) 176-188.